



Information capacity of electronic vision systems

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Abstract

The comparison of various electronic–optical vision systems has been conducted based on the criterion ultimate information capacity, C , limited by fluctuations of the flux of quanta. The information capacity of daylight, night, and thermal vision systems is determined first of all by the number of picture elements, M , in the optical system. Each element, under a sufficient level of irradiation, can transfer about one byte of information for the standard frame time and so $C \approx M$ bytes per frame. The value of the proportionality factor, one byte per picture element, is referred to systems of daylight and thermal vision, in which a photocharge in a unit cell of the imager is limited by storage capacity, and in general it varies within a small interval of 0.5 byte per frame for night vision systems to 2 bytes per frame for ideal thermal imagers. The ultimate specific information capacity, C^* , of electronic vision systems under low irradiation levels rises with increasing density of optical channels until the number of the irradiance gradations that can be distinguished becomes less than two in each channel. In this case, the maximum value of C^* turns out to be proportional to the flux of quanta coming from an object under observation. Under a high level of irradiation, C^* is limited by diffraction effects and amounts to $1/\lambda^2$ bytes/cm² frame.

Keywords: Electronic-optical systems; Night vision systems; Thermal imagers; Information capacitance; Photon fluctuations

1. Introduction

The design of electronic-vision and other systems involves the optimisation of many tactical and technical parameters. Optimization of the information capacity — the most important parameter of electronic-vision systems according to Rose [1] — leads to very different considerations and results from the standard ones [2]. We will calculate the ultimate information capacity of electronic-vision systems limited by photon fluctuations, find the diminishing factors in this and show the ways to reduce these losses.

2. Expressions for calculation of information capacity of electronic vision systems

According to Rose's concept of the ultimate resolution limited by photon fluctuations [1] and Shannon's definition of the information capacity [3], the authors of Ref. [4] used the following relationship for calculation of the ultimate information capacity per frame, C , of electronic-vision systems, expressed in bytes:

$$C = \frac{M}{8} \log_2 \left[\frac{1}{k_0} \sin \left(\frac{\beta}{2} \right) \sqrt{\frac{\eta}{F} A_e t_i N_e} \right] \\ = 0.415 M \log \left[\frac{1}{k_0} \sin \left(\frac{\beta}{2} \right) \sqrt{\frac{\eta}{F} A_e t_i N_e} \right]. \quad (1)$$

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The notation introduced and necessary comments on them will now be described:

(1) M is the number of the picture elements in the focal plane image of an object. It should not be confused with the number of photosensitive unit cells (photosensitive elements) in a photodetector device. The number of these unit cells will be denoted by M_e hereafter. Naturally, one and the same number of the picture elements in a frame can be obtained using a staring two-dimensional (2D) array photodetector as well as a scanned linear-array or even single-element detector device. In the last cases, the number of cells, $M_e \geq 1$, is considerably less than the number of picture elements, M . So for example, a square frame image consisting of $M = m \times m$ picture elements can be examined either with the use of a 2D array detector with the same number of unit cells, $M_e = M = m^2$, or by one-dimensional scanning of a linear array detector with $M_e = m$. In case a 2D array detector and a linear one having an equal numbers of cells, M_e , are used, the former decomposes the image into $M = M_e$ elements and the latter decomposes it into a much greater number of elements, in particular, into $M = M_e^2$ elements if the scanning direction is perpendicular to the linear array and the frame is square. These typical examples will be analyzed below while maximizing the C value. It is not difficult to obtain the relationship between M and M_e for other cases, particularly, for linear multi-row detector arrays or SPRITE devices.

(2) k_0 is the minimum signal-to-noise ratio in a unit cell at which the permissible errors in signal measurement (the errors of non-detection and false alarm) are ensured [1].

(3) β is the angle of the projection of the objective or the plane angle at which a photosensitive unit cell 'sees' the exit pupil of the objective. According to this, $\beta/2$ is the back aperture angle of the objective. If the distance from an observed object is much greater than the linear dimensions of the objective, then the image is projected practically in the focal plane and the sine of the said angle is determined by the diameter of the exit pupil, D' , and the focus distance, f :

$$\sin \frac{\beta}{2} = \frac{D'/2f}{\sqrt{1 + (D'/2f)^2}}. \quad (2)$$

Often, the approximation $\sin(\beta/2) \approx D/2f$ is used, where D is the diameter of the entrance pupil of the objective.

(4) η is the effective quantum yield of a unit cell taking into account the losses in a photosensitive element and the ratio of the element area to the area of a picture element (additional losses arise if the element area is less than that of a picture element). In general, the losses in the optical and scanning systems, etc. can be taken into account with the use of the factor η as well.

(5) F is the noise factor. When the radiant noise is dominant (and this case of BLIP detection [1] will be considered here), F changes within a small interval depending on the spectral range of a photosensitive element [5,6]. A value of $F = 1$ corresponds to the short-wavelength radiation (the energy of the photon, $h\nu$, is greater than the thermal energy kT), for which the noise is the Poisson's one. $F = 1.37$ corresponds to the total radiation of a blackbody source in the whole spectral range of 0 to ∞ and is conditioned by extra-Poisson noise under grouping of the photons with the low energy values, $h\nu \ll kT$.

(6) A_e is the area of a unit cell (a photosensitive element), determining the area of a picture element in the focal plane as well. With the total number of picture elements equal to M , the frame area, A_f , i.e., the area of the image in the focal plane, is:

$$A_f = MA_e. \quad (3)$$

The area of a picture element in the two cases considered above is related to the area of the frame by:

$$A_e = \frac{A_f}{M} = \frac{A_f}{M_e} \quad (4)$$

in a 2D array, and by

$$A_e = \frac{A_f}{M} = \frac{A_f}{M_e^2} \quad (5)$$

in a linear array.

(7) t_i is the time for integration of a signal (a charge) for each picture element of the image. In electronic vision systems, the frame time, T_f , is

usually set at the value which is intended for the analysis of a given image. In a 2D array, with $M = M_e$, a signal from each picture element is formed in its individual cell, which is why this signal can be integrated practically for the whole frame time and $t_i \approx T_f$. With $M_e < M$, particularly for a linear array, for the intended time T_f , one unit cell should examine $m = M/M_e$ picture elements, therefore, the integration time cannot be more than

$$t_i = \frac{T_f}{m} = \frac{M_e}{M} T_f. \quad (6)$$

In the system with a square frame considered above, we have:

$$t_i = \frac{M_f}{M_e^2} T_f = \frac{T_f}{M_e}. \quad (7)$$

(8) N_e is the maximum (for a given system and conditions of observation) quantity of the effective photons emitted and reflected by a unit of object area per time unit. The term ‘effective’ signifies that the value N_e is determined for the limited spectral range, $\lambda_s - \lambda_m$, of a photosensitive element, where λ_s and λ_m are the short and the long cutoff wavelengths of the element respectively. The total number of quanta in the whole spectrum of the object radiation will be denoted by N . Naturally, $N_e = N$ only for the unlimited spectral range of a sensitive element (λ from 0 to ∞).

The structure of Eq. (1) is obvious. If the density of effective quanta emitted by an object is N_e (in the range $\lambda_s - \lambda_m$), then in the focal plane and without taking into consideration the losses in the objective, it amounts to $N_e \sin^2(\beta/2)$: the object radiation is as usually assumed to follow the Lambert’s law [2]. So, the term $\sin^2(\beta/2)$ is the coefficient of collection (transference) for an ideal objective. For the time t_i , $n_e = t_i A_e N_e \sin^2(\beta/2)$ quanta get to the area A_e and the photosensitive element registers only the fraction η . And just this quantity, $n_s = \eta n_e$, is a signal. The intrinsic (radiant) noise of the number of quanta obtained is equal to $n_n = \sqrt{F \eta n_e}$. The system is capable of distinguishing (with permissible errors) the increment in signal that is k_0 times the noise,

$k_0 n_n = k_0 \sqrt{F \eta n_e}$, i.e., the number of the levels (gradations) of signal that can be distinguished are

$$\begin{aligned} K &= \frac{n_s}{k_0 n_n} = \frac{\eta n_e}{k_0 \sqrt{F \eta n_e}} = \frac{1}{k_0} \sqrt{\frac{\eta n_e}{F}} \\ &= \frac{1}{k_0} \sin(\beta/2) \sqrt{\frac{\eta}{F} A_e t_i N_e}. \end{aligned} \quad (8)$$

According to Shannon, just the binary logarithm of this number is a measure of the information capacity of a unit cell expressed in bits, i.e., it amounts to the number of bits, b , that is required to express the number K in the binary system: $K \approx 2^b$. Hence, the number of bytes equals $b/8 = (\log_2 K)/8$. Each picture element is an individual (independent) optical channel of information transference in fact. The information capacity of a multi-channel optical system is determined by the sum of those of M channels hence it is equal to $(M \log_2 K)/8$ bytes. So, we obtain from Eq. (8) Eq. (1).

Note that the number K can also be considered as the maximum signal-to-noise ratio for a picture element (the dynamic range of a picture element) normalized to the required ratio k_0 .

The expression for C from Eq. (1) presented above characterizes capabilities of a vision system in information capacity. When deriving, the noise was supposed to be limited by the fluctuations of the flux n_e of photons which cannot be removed in principle and the density of emission from each element of an object to take any value from zero to N_e . As nominal values of the N_e , we will choose its statistical values for each electronic vision system (Section 3). Just the consideration of the described model is first of all the subject of the present paper. Naturally, images of real objects are determined by features of these objects and conditions of observation. The effect of some factors on the volume of the information transferred via the image is discussed in Section 8.

The dependence of Eq. (1) of the information capacity C on all the parameters of the problem is so obvious that the traditional order of setting forth can be violated and a number of conclusions can be formulated at once.

The value C being proportional to M , in order to increase C , the number of picture elements, M (and just the picture elements, but not the unit cells in the photodetector device) should be increased first of all. The rest of the parameters of the system $[\eta, t_i, N_e, \sin(\beta/2), F]$ enter into the relationship for C under the logarithm symbol and so they influence C far weaker. Therefore, one can set no strict requirements to the quantum yield and use not only 2D array detectors but linear ones as well. The principal difference of a linear array detector from the 2D one concerning signal processing consists in decrease of t_i , and this time, as we noted just above, weakly influences the value C . A linear array can be even more preferable than the 2D array: if the use of it creates great possibilities for additional increase of the number of picture elements as in the example considered above.

Since the information capacity C weakly depends on N_e , it also changes little on variations of the spectral range, $\lambda_s - \lambda_m$, the total number of photons, N , and even the source of radiation (up to reasonable limits) if only the numbers of picture elements, M , in the vision systems compared are equal to each other.

Let us corroborate the conclusions formulated above with concrete numerical calculations. In order to do this, it is convenient to modify Eq. (1) for the capacity C and to separate the terms in this relationship determining the value C for an ideal photodetector device from the terms expressing losses of C in real devices. An ideal device should register all the quanta incident upon it and bring no additional noise, then the normalized signal-to-noise ratio K and, consequently, the value $C \sim \log K$ will be maximum. These conditions are valid with:

- the quantum yield to be $\eta = 1$;
- the maximum integration time, $t_i = T_f$, i.e., with the use of a 2D array with $M_e = M$;
- the spectral range of the photosensitive element to be infinitely wide, i.e., extended from 0 to ∞ , then $N_e = N$;
- BLIP detection to take place.

Let us express $\log K$ in Eq. (1) in terms of the said parameters, T_f, N :

$$C = 0.415M \left\{ \log \left[\frac{1}{k_0} \sin \left(\frac{\beta}{2} \right) \sqrt{\frac{A_e T_f N}{F_0}} \right] \right.$$

$$\left. - \frac{1}{2} \log \frac{T_f N}{\eta t_i N_e} + \frac{1}{2} \log \frac{F_0}{F} \right\}. \quad (9)$$

The meaning of the proposed relationship, Eq. (9), is clear. In an ideal photodetector device, $T_f N / (\eta t_i N_e) = 1$, $F_0 / F = 1$, which is why the two last logarithms turn into zero and so the first logarithm determines the maximum value of C . In a real photodetector device $T_f N / (\eta t_i N_e) > 1$, therefore, the second logarithm determines the level of losses in the value C . The maximum value of the third term,

$$\max \frac{1}{2} \log \frac{F_0}{F} = \frac{1}{2} \log 1.37 = 0.07, \quad (10)$$

is much less than the values of the first two ones (the following evaluations give 3.0–4.5 for them) and so the last logarithm can be neglected hereafter.

Let us start the analysis from the comparison of the C values for diverse electronic vision systems.

3. Information capacity of daylight, night, and thermal vision systems

3.1. Daylight vision systems

In daylight vision systems, the image of an object is formed by the direct and diffused radiation of the sun reflected from this object. In Ref. [4], a technique is described for the calculation of the flux density, N , of the quanta reflected from vertical objects situated near the surface of the earth on its illuminated hemisphere.

The technique is based on the statistical data of Refs. [7,8] on the radiant balance of the earth. The radiation of the sun was calculated in Ref. [4] as a blackbody source at a temperature of $T_s = 5785$ K. Thereafter, the density of quanta at the sunlit boundary of the atmosphere was found. The earth surface is reached by, on the average, 0.3 of the sun radiation in the form of directly incident sun radiation and additionally 0.18 of this radiation is in the form of atmosphere-diffused radiation [7,8]. If the fact is taken into account that the area of sunlit earth hemisphere is twice as large as the cross section area from which the sun radiation is collected for the earth and the mean value of the daylight irradiance

for vertical objects is about 1.5 more than for horizontal ones [4], then we obtain

$$\frac{0.3 + 0.18}{2} \times 1.5 = \frac{1}{2.78}. \quad (11)$$

Thus, the flux of quanta near the surface of the earth turns out to be less than that on the sunlit boundary of the atmosphere: by a factor of 2.78 for vertical objects and averaged day conditions. With the maximum value of reflectance, $R = 1$, such a technique leads to the value

$$N = 2.29 \times 10^{17} \text{ cm}^{-2} \text{ s}^{-1}. \quad (12)$$

For subsequent evaluations, it is reasonable to take T_f to be equal to the time of the TV frame, $4 \times 10^{-2} \text{ s}$. The area of an element (unit cell) typical of multielement photodetector devices is $A_e = 30 \times 30 \mu\text{m}^2 = 9 \times 10^{-6} \text{ cm}^2$. Let us take a conditional objective with the relative opening hole of $D:f = 1:1$, then $\sin(\beta/2) \approx 0.45$. The required value of $k_0 = 5$ [1]. Substituting the assumed numerical values of the parameters for the system into Eq. (9), we obtain:

$$\begin{aligned} C &= 0.415 M \left(4.34 - \frac{1}{2} \log \frac{T_f N}{\eta t_i N_e} \right) \\ &= 1.8 M \left(1 - 0.115 - \log \frac{T_f N}{\eta t_i N_e} \right). \end{aligned} \quad (13)$$

3.2. Night vision systems

For night vision systems, evaluation of the information capacity, C , was based on the data of Ref. [9], in which the irradiance of the earth is from the stars in the absence of the moon and clouds. From this the maximum density of quanta can be calculated: it turns out to be equal to

$$N \approx 10^{11} \text{ cm}^{-2} \text{ s}^{-1}. \quad (14)$$

At this value of N , the expression for the information capacity C in Eq. (11) is:

$$C = 0.51 M \left(1 - 0.4 \log \frac{T_f N}{\eta t_i N_e} \right). \quad (15)$$

3.3. Thermal vision systems

For the calculation of C , let us assume that the maximum value of N corresponds to the thermal

radiation of a blackbody source at the temperature equal to the averaged temperature of the earth according to the thermal radiation $T_E = 293 \text{ K}$ [4]. According to the Stefan–Boltzmann law for a flux of particles [10]:

$$\begin{aligned} N &= \sigma_n T_E^3 = 1.52 \times 10^{11} (293)^3 \\ &= 3.82 \times 10^{18} \text{ cm}^{-2} \text{ s}^{-1}. \end{aligned} \quad (16)$$

Substituting this value into Eq. (9), we obtain:

$$C = 2 M \left(1 - 0.1 \log \frac{T_f N}{\eta t_i N_e} \right). \quad (17)$$

Certainly, the values of the parameters A_e , T_f , $\sin(\beta/2)$, k_0 can change from one system to another and differ from the nominal values assumed above, therefore, the numerical factors in Eqs. (13), (15), and (17) are not a dogma yet, but they are near to a dogma! Firstly, variations of the said parameters are insignificant as compared with the variation of N [usually, $A_e \approx 10 \times 10 - 50 \times 50 \mu\text{m}^2$, the relative aperture is 1:1–1:2, and so $\sin(\beta/2) \approx 0.45 - 0.24$]. Secondly, a logarithmic dependence smoothes variations of these parameters. For the typical limits of variations of the parameters, the variation of the numerical factors in the relationships for C of daylight and thermal vision systems, Eqs. (13), (17), falls inside the limits of $\pm(2-8.6)\%$ and that in the relationship for a night vision system, Eq. (15), lies within an interval of $\pm(9-30)\%$.

The relationships (13), (15), and (17) make it possible to evaluate the information capacity of the three systems. The value C reaches its maximum value, naturally, with the use of both an ideal objective and an ideal 2D array detector accommodated with a source of radiation in the spectral range and is determined by the first co-multiplier in the relationships given above.

The greatest flux N of quanta takes place in thermal vision and the information capacity of this system is therefore theoretically the highest, all other conditions being equal. From Eq. (17), a handy rule follows: the ultimate information capacity of one frame in an ideal thermal imager equals double the number of picture elements:

$$C = 2 M \text{ bytes}. \quad (18)$$

In daylight vision, the value N decreases by more than an order of magnitude, but since C weakly

depends on N ($C \sim \log N$), a decrease of the capacity C itself does not exceed 10% [compare Eqs. (13) and (17)].

A larger decrease of C takes place in night vision systems: it is one fourth as high. But if the fact is taken into account that the flux of quanta, N , decreases by $7\frac{1}{2}$ orders of magnitude here, then such a decrease of C does not really seem to be excessive.

As can be seen, even under a very low flux of quanta (ca. $10^{11} \text{ cm}^{-2} \text{ s}^{-1}$), the potential of the image field turns out to be sufficient for the operation of an electronic vision system (night vision). And here, it is natural to put the question: what is the minimum flux of quanta, $N_{\min}$, with which the image will be still formed in the electronic vision systems described that is sufficient for the transfer of information?

Let only two logical states, 'zero' and 'unity', be transferred through each optical channel, which corresponds to two gradations in the image, i.e., K appears to take the minimum possible value, $K_{\min} = 2$. It is evident that such an electronic vision system is capable of transferring brightnesses of grey surfaces as well on account of the fluctuation of the density of signals 'zero' and 'one'. With the typical system parameters assumed including $A_e = 9 \times 10^{-6} \text{ cm}^2$ and with an ideal photodetector device ($\eta = 1$, $t_i = T_f$), we obtain:

$$K_{\min} = \frac{\sin(\beta/2)}{k_0} \sqrt{A_e T_f N_{\min}} = 2,$$

$$N_{\min} = \frac{4k_0^2}{A_e T_f \sin^2(\beta/2)} = 1.4 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}. \quad (19)$$

This evaluation is significant: it permits the information 'reserve of robustness' of a vision system to be determined. Daylight and thermal vision systems possess a firm 'reserve of robustness': the ratios $N/N_{\min}$ are 1.6×10^8 and 2.7×10^9 , respectively. Therefore, some losses, and they can be appreciable, are permissible when registering such a great amount of quanta, N , which we will see below. In a night vision system, the 'reserve of robustness' is practically exhausted: the excess of N over $N_{\min}$ is not even two orders of magnitude. There is nowhere to 'retreat' in this case: no appreciable decreases in N

are permissible here. It follows from the above statement that for the daylight and thermal vision systems an photosensitive element area of ca. $30 \mu\text{m}$ can be called high-level and for night-vision systems as low-level.

A conditional boundary between high and low levels, N_0 , can be introduced: in particular, it can be taken that at a high level ($N \geq N_0$), one channel is capable of transferring not less than a byte of information. Then,

$$K = \frac{\sin(\beta/2)}{k_0} \sqrt{A_e T_f N_0} = 2^8,$$

$$N_0 = \frac{2^{16} k_0^2}{A_e T_f \sin^2(\beta/2)} \approx 2 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}. \quad (20)$$

The priorities in C , namely, thermal vision, a daylight vision system, and a night vision system, are valid with the use of not only ideal photodetector devices but real ones as well. So with one and the same value of $T_f N / (\eta t_i N_e) = 10$, the value C turns out to be in these systems 10, 11.5, and 40%, respectively [compare Eqs. (17), (13), and (15)].

Let us consider successively the main causes that lead to an increase of C in real systems.

4. Spectral range and information capacity

It is obvious that the spectral range of a photodetector device must be accommodated with the spectrum of radiation of the sources: the sun ($0.2\text{--}2 \mu\text{m}$), the stars ($0.5\text{--}1.9 \mu\text{m}$), or the thermal radiation of the earth ($3\text{--}40 \mu\text{m}$). Under real conditions, the spectral range of a photodetector device is limited, which is why only a part of quanta, N_e , of the total radiation flux N turns out to be registered. Let a photodetector device be an ideal one concerning the rest of the parameters: the quantum yield $\eta = 1$, the integration occurs in the course of the whole frame time, $t_i = T_f$.

The technique for the calculation of the capacity C is obvious in this case. Integrating the Planck's distribution in the interval $\lambda_s\text{--}\lambda_m$ (Table 1), we find the N_e , calculate the value $\log N/N_e$, and then the coefficient of the use of information capacity, $C(\lambda_s\text{--}\lambda_m)/C(0\text{--}\infty)$, i.e., the term in the parentheses of

Eqs. (13), (15), and (17). The values of N_e and $C(\lambda_s - \lambda_m)/C(0 - \infty)$ obtained with the use of such a technique are given in Table 1. There typical spectral ranges are for electronic systems of daylight vision 0.45–0.95 μm (silicon), for thermal vision it is 3–5 μm (InSb, PtSi, HgCdTe) and 8–14 μm (HgCdTe). In the examples under consideration, a sensitive element registers one third–one four hundredth fraction of the entire amount of quanta only, but owing to a ‘logarithmic influence’, the information capacity decreases only by 6% to 26% in these cases. One more result unusual for developers of thermal imagers follows from Table 1: the photodetector devices intended for the ranges 8–14 and 3–5 μm are identical regarding the value C : the difference does not exceed 20%.

5. Dependence of information capacity on quantum yield, number of channels, and configuration of two-dimensional array

Similarly, one can evaluate the losses in C , resulting from the rest of the factors in Eq. (1).

The quantum efficiency of intrinsic photoconductive and photodiode detectors in the spectral range usually lies within the limits of $\eta = 0.3$ to 0.9 and with such values of η , the coefficient to use for C for daylight and thermal vision systems is equal, according to Eqs. (13), (17),

$$\frac{C(\eta)}{C(1)} = 1 - 0.1 - 0.115 \log \frac{1}{0.3-0.9} = 0.94-0.995. \quad (21)$$

Thus, the question: how much the quantum efficiency of the detectors in these systems influences C can be answered: in fact not at all.

Decrease of C is more appreciable with very small values of η , in particular in the thermal imagers based on Schottky-barrier detectors. In such detectors, values of $\eta \approx 10^{-2}$ are possible [6,11]. According to Eqs. (13) and (17), the coefficient becomes 0.77–0.8 in this case.

Similar losses in C are observed in night vision systems, even if the photodetector devices with a relatively high value of $\eta = 0.3-0.9$ are used in them:

$$\frac{C(\eta)}{C(1)} = 1 - 0.4 \log \frac{1}{0.3-0.9} = 0.79-0.98. \quad (22)$$

Through the dependence $C(t_i)$, the influence of the number of picture elements (optical channels) and the detector configuration on the information capacity can be observed. It was noted above that for an ideal 2D array detector, $t_i = T_f$ and for an ideal linear array detector, the ultimate possible integration time is $t_i = T_f/M_e$, i.e., it is determined by Eq. (7). The latter relationship was written for the simplest model of a square frame, $M = M_e \times M_e$. Taking these values into account and according to Eqs. (13) and (17), we obtain for systems of daylight and thermal vision (for one and the same numbers of picture elements, M , in linear and 2D arrays):

$$\begin{aligned} \frac{C(\text{lin. array})}{C(2\text{D array})} &= 1 - (0.1-0.115) \log \frac{T_f}{t_i} \\ &= 1 - (0.1-0.115) \log M \\ &= 0.69-0.8 \end{aligned} \quad (23)$$

The numerical comparison in Eq. (23) was conducted for linear arrays with a number of unit cells of 100 to 500 and for 2D arrays of 100×100 to 500×500 . Even if a developer replaces such a linear array with the 2D one (i.e., increases the number of

Table 1
Losses in information capacity under the limitation of spectral range

	System						
	Daylight vision			Night vision	Thermal vision		
$\lambda_s - \lambda_m$ (μm)	0– ∞	0.45–0.95	The eye	0– ∞	0– ∞	8–14	3–5
N, N_e ($\text{cm}^{-2} \text{ s}^{-1}$)	2.3×10^{17}	7.6×10^{16}	2.3×10^{16}	10^{11}	3.8×10^{18}	8.5×10^{17}	10^{16}
$C(0, \infty)$ (bytes/frame)	1.8M	–	–	0.5M	2M	–	–
$C(\lambda_s - \lambda_m)/C(0, \infty)$	1	0.94	–	1	1	0.94	0.74

channels by a factor 100 to 500), then a gain by only 20% to 31% will be obtained! It is unlikely that such efforts can be considered as reasonable ones. Thus, we have come to the next non-trivial result: when designing daylight and thermal vision systems with a criterion of information capacity, the perfect ‘emancipation’ of the linear array occurs.

However, a linear array is unfit for image transfer in night vision systems because there results too short a dwell time, it is M_e^{-1} as great as that in the 2D array [see Eq. (7)], intended for integration of a weak signal from each picture element. This is equivalent to the reduction of the average (over the frame time) flux of quanta by the same factor of M_e :

$$\bar{N} = \frac{N}{M_e} = \frac{10^{11}}{100-500} = (0.2-1) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}. \quad (24)$$

Here, $N = 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$ [from Eq. (14)], $M_e = 100-500$. The calculated value of $\bar{N}$ turned out to be less than the permissible minimum, $N_{\min}$, from Eq. (19): for the linear array, the ‘reserve of robustness’ turned out to be insufficient!

Hitherto, photodetector devices with the identical photosensitive areas A_e have been compared. Another model that is close to the real situation may be considered. Let a transfer of the image of an assigned area A_f , be required, and the system of switching followed by a signal-processing system limits the number of unit cells (photosensitive elements) to some value, M_e . Then a developer has two main options to construct the system. The first is to occupy the whole frame area, A_f , with a 2D array of the number of unit cells equal to M_e . In this case, the number of picture elements is limited by the ultimate possible number of unit cells, $M = M_e$, with A_e being equal to A_f/M_e [see Eq. (4)] and $t_i = T_f$. The second option is: to scan the A_f area with the linear array having the same number of unit cells, M_e . This makes it possible to increase the number of picture elements considerably: for a square frame, $M = M_e \times M_e$. However, the element area and the integration time decrease: $A_e = A_f/M_e^2$ [Eq. (5)], $t_i = T_f/M_e$ [Eq. (7)]. As can be seen, in such a model, the 2D array cannot compete with the linear one at all: it yields to the latter in the number M by a factor of M_e and consequently, in the information capacity

almost by the same factor of M_e . ‘Almost’: because the values A_e and t_i in the 2D array are, however, higher. A precise calculation of the values C for systems based on the photodetector devices under consideration can be conducted with the use of Eq. (1). Substituting the said values of M , A_e , t_i into this equation, we will obtain: for a vision system based on the 2D array:

$$\begin{aligned} C_{(2D)} &= 0.415 M_e \log \left(\frac{1}{k_0} \sin(\beta/2) \sqrt{\frac{\eta}{M_e} A_f T_f N_e} \right) \\ &= 0.415 M_e \left[\log \left(\frac{1}{k_0} \sin(\beta/2) \sqrt{\eta A_f T_f N_e} \right) \right. \\ &\quad \left. - \frac{1}{2} \log M_e \right] \end{aligned} \quad (25)$$

for that based on the linear array:

$$\begin{aligned} C_{\text{lin. array}} &= 0.415 M_e^2 \log \left(\frac{1}{k_0} \sin(\beta/2) \sqrt{\eta A_f T_f N_e} \right) \\ &= 0.415 M_e^2 \left[\log \left(\frac{1}{k_0} \sin(\beta/2) \sqrt{\eta A_f T_f N_e} \right) \right. \\ &\quad \left. - \frac{3}{2} \log M_e \right]. \end{aligned} \quad (26)$$

The ratio of these values is equal to:

$$\begin{aligned} \frac{C_{(2D)}}{C_{(\text{lin. array})}} &= M_e \frac{1 - (0.19-0.23) \log M_e}{1 - (0.064-0.076) \log M_e} \\ &\approx M_e (1 - (0.13-0.15) \log M_e) \\ &= (0.5-0.65) M_e. \end{aligned} \quad (27)$$

The argument of the logarithm has been calculated, naturally, for high-level systems: $N_e = 10^{16} - 3.82 \times 10^{18}$ at $\eta = 1$. The frame area was taken as $A_f = 2 \times 2 \text{ cm}^2$, and the values T_f and $\sin(\beta/2)$ have not been changed. From Eq. (27), a value of the above-noted ‘almost’ is seen: with $M_e = 500-2000$, the linear array surpasses the 2D one in information capacity if not by a factor of M_e then by $M_e/2$.

6. Electric capacity of charge storage

In all the cases analyzed above, finally, the amount of the effective quanta detected by a photosensitive

element, $n_s = \eta A_e t_i N_e \sin^2(\beta/2)$, was varied. The density of these quanta per unit of the element area in the systems of daylight and thermal vision considered above changes within the limits

$$\left(\frac{n_s}{A_e}\right)_{\min} = \sin^2\left(\frac{\beta}{2}\right) \eta t_i N_e = \sin^2\left(\frac{\beta}{2}\right) \eta \frac{T_f}{M_e} N_e$$

$$= 0.202 \times 0.3 \frac{4 \times 10^{-2}}{500} 10^{16}$$

$$\approx 5 \times 10^{10} \text{ cm}^{-2}, \quad (28)$$

$$\left(\frac{n_s}{A_e}\right)_{\max} = \sin^2\left(\frac{\beta}{2}\right) T_f N_e$$

$$= 0.202 \times 4 \cdot 10^{-2} \times 3.82 \times 10^{18}$$

$$\approx 3 \times 10^{16} \text{ cm}^{-2}. \quad (29)$$

The minimum density of quanta, Eq. (28), was obtained, in the present paper, for a linear array of photosensitive elements with the spectral range 3–5 μm and for the frame format 500×500 . The maximum density of quanta, Eq. (29), was obtained for an idealized 2D array with the infinitely wide spectral range ($N_e = N$). It was supposed that the photodetector device was capable of registering all the effective quanta, n_s , incident upon a photosensitive element, therefore, it was n_s that was used in the calculation of C with Eq. (1).

Up-to-date photon focal-plane array devices include charge storage cells. Are they able to accumulate the charge corresponding to the said amount of quanta n_s ? In order to answer this question, let us evaluate the maximum density of electrons that can be accumulated in the storage capacitor of a semiconductor CCD or MOS unit cell:

$$n^* = \frac{c^* U}{q} = \frac{2 \times 10^{-8} (1-10)}{1.6 \times 10^{-19}} \approx 10^{11} - 10^{12} \text{ cm}^{-2}. \quad (30)$$

Here, $q = 1.6 \times 10^{-19}$ C is the electron charge. In order to simplify the calculation, the areas of a storage capacitor, a picture element, and a photosensitive unit cell are assumed to be equal. The specific value of the capacitance equal to $c^* \approx 2 \times 10^{-8}$ f/cm² is typical for a CCD, in a 2D array with MOS multiplexers it can be somewhat higher [12]. The taken interval of voltage variation, $U = 1-10$ V, is also typical for CCD and MOS 2D arrays.

Comparison of Eqs. (28), (29), and (30), shows that the ultimate charge registered in a photodetector device is limited by the capacitance of a storage cell: only in a linear array with range 3–5 μm , it can be sufficient for the accumulation of the necessary charge. And in a 2D array at a high flux of quanta, n_e , special measures have to be taken (in particular, division and skimming of charge, external frame-after-frame accumulation) in order to ensure the required dynamic range. Exactly because of the said limitation, in IR 2D arrays based on HgCdTe (8–14 μm), one is still limited by a row integration ($t_i = T_f/M_e$). Note that in IR 2D CCD based on Schottky barriers for the range 3–5 μm , n_s decreases not only through a shift of spectral range, but also because of a small quantum yield ($\eta \approx 0.01$).

In previous sections, we noted that the information capacity of high-level vision systems can be influenced, although this influence is weak, by a number of factors: the type of a source (the sun, thermal radiation), the spectral range and quantum yield of a photosensitive element, the configuration of photosensitive elements (a linear or 2D array). But even a weak influence of these factors on C can be revealed only after the increase of the capacitance of a storage cell by many orders of magnitude: up to $10^{16} - 10^{17}$ electrons/cm² [Eq. (29)]. However, at present, the limitation in principle in the information capacity of high-level systems with focal-plane photon detectors is set by the electric capacitance of a storage cell. This capacitance smooths the distinctions in the parameter C among vision systems and completely removes the influence of the factors mentioned above: spectral range, level of sensitivity, and configuration, naturally, in real limits of their variation.

Thus, in all the considered systems with a high level of irradiation ($n_s > A_e n^*$), a unit cell of the photodetector device is able to accumulate a quantity of electrons equal to $A_e n^*$ only. Therefore, in the initial relationship for C in Eq. (1), the number of quanta detected by a unit cell, $n_s = \eta t_i A_e N_e \sin^2(\beta/2)$, should be substituted by the quantity of accumulated electrons, $A_e n^*$. This results in

$$C = 0.415 M \log \left[\frac{1}{k_0} \sqrt{A_e n^*} \right] \approx M. \quad (31)$$

The numerical evaluation was conducted for the above-assumed values of k_0 , A_e , and also the mean value $n^* = 3 \cdot 10^{11} \text{ cm}^{-2}$ [Eq. (30)].

It follows from Eq. (31) that with the limitation of a photocharge from each photosensitive element by the electric capacitance of a real storage cell, no more than one byte of information can be transferred through one optical channel for the frame time. This value was taken above as a conditional boundary N_0 between low and high-level electronic vision systems [see Eq. (20)]. It is easy to find that $n^* \approx N_0 T_f \sin^2(\beta/2)$.

In the very beginning of this paper, just after having written the relationship for C in Eq. (1), we saw its principal feature: C is proportional to M and the rest of the parameters weakly influence the value C . The further analysis has only defined the proportionality factor, i.e., the number of bytes per picture element more precisely. For typical parameters of vision systems, the information capacity of one element does not exceed 2 bytes (thermal vision, an ideal photodetector device [Eq. (18)]). The daylight and thermal vision systems with real photodetector devices yield in C to the systems based on ideal detector devices by about a factor two (for the identical values of A_e and M) and with the format of $500 \times 500 = 2.5 \times 10^5$, they are able to transfer the quantity of information per frame equal to $C \approx M = 2.5 \times 10^5$ bytes. (32)

Accordingly, in high-resolution vision systems, $M \approx 1000 \times 1000$ elements per frame, the capacity C reaches values on the order of 10^6 bytes. It is pertinent here to repeat the conclusion: it is unreasonable to waste efforts for improvement of the unit cell to enhance information capacity only: even if increasing c^* by a factor of 10^6 , we increase C only by a factor of two, being the theoretical limit. Thus, the main way to increase C consists in an enlargement of the format.

The night vision system is different. In this low-level system, the flux of quanta is small even for the whole frame time ($t_i = T_f$),

$$\frac{n_s}{A_e} = N_e T_f \sin^2(\beta/2) = 10^{11} \times 4 \times 10^{-2} \times 0.202$$

$$= 8 \times 10^8 \text{ cm}^{-2} \quad (33)$$

therefore, the capacitor of a unit cell is able to accumulate such a number of electrons [Eq. (30)].

Thus, the conditional division of electronic vision systems into low and high-level ones [Eq. (20)] acquires an additional physical sense: in up-to-date focal-plane arrays with photon sensitive elements under high-level operation mode, the photocharge integrated for the frame time overfills the 'well' of the CCD or MOS storage cell. In these cases, when designing electronic vision systems, special measures are being taken to restrict the irradiation or the photocharge.

In summary: a limited storage cell does not make it possible to realize completely the capabilities of daylight and thermal vision systems $[(1.8-2)M]$ in information capacity and decreases this capacity to values of M [Eq. (31)]. As a result, in the value C , these systems approach night vision systems, for which $C \approx (0.4-0.5)M$ [Eqs. (15) and (22)].

7. Electronic vision systems and detection

Detecting systems are usually characterized by their sensitive parameters, in particular, the noise equivalent power (NEP). The requirements for a photodetector device when designing an electronic vision system based on the criterion of the achievement of the maximum value of C turn out to be less demanding than those based on the criterion of the minimum NEP. That same logarithmic dependence, $C \sim \ln K$, is 'guilty' here: it damps the losses in signal-to-noise ratio while those in NEP turn out to be exactly the same as those in K ($\text{NEP} \sim 1/K$). In order for the maximum value K to be ensured in detecting systems, strict requirements have to be set for the quantum yield: in fact, its decrease from 1 to 0.3 results in a change for the lowest NEP value by 80% ($\text{NEP} \sim 1/\sqrt{\eta} = 1/s\sqrt{0.3} = 1.83$). It should be recalled that C gets lower by ca. 6% only, in this case [see Eq. (21)].

In detecting systems, linear arrays tend to be substituted by 2D arrays: theoretically, this improves NEP by a factor of $\sqrt{M_e} = \sqrt{100-500} = 10-24$ [1,7]. In high-level systems, such a rather complicated substitution is not necessary [see Eq. (23)]. Moreover, there are situations described above where the linear array considerably surpassed the 2D array.

The spectral range is the third factor considered above. We have seen that the transition from the range 3–5 μm to 8–14 μm almost does not increase

the information capacity although the effective number of quanta rises by a factor of 85 (see Table 1). With the use of IR detecting systems: thermal search and tracking systems and thermal imagers, an object very weakly overheated against the background could be detected. Since $K \sim \sqrt{N_e}$, with the said increase in the number of the effective quanta, the signal-to-noise ratio increases by a factor $\sqrt{85} \approx 9$, and as a consequence, the rise of temperature sensitivity, i.e., the minimum difference in temperature equivalent to the noise, can be expected to be ca. 9 also. However, precise calculation shows that this improvement is equal to a factor of 5.5 [6].

If both requirements, namely, to obtain the minimum NEP and the maximum C with the spatial resolution (or the photosensitive element area A_e) fixed, must be satisfied, then a photodetector device has to be designed following the stricter criterion of minimum NEP.

The conclusions made above in this section were formulated for the detector device with unlimited capacitance of the storage cell. Taking into account the fact that this capacitance is finite, distinctions in approaches to designing of the focal-plane detector devices for vision and detecting systems disappear. So, we have seen that taking this into account the distinctions between spectral ranges is reduced: detector devices intended for 3–5 and 8–14 μm ensure one and the same value of C . The electric capacitance of a unit cell in photon 2D arrays limits the ultimate accumulated charge, $\eta A_e t_i N_e \sin^2(\beta/2) \leq A_e n^*$ [Eq. (30)], and hence it limits the maximum signal-to-noise ratio, $Kk_0 \leq \sqrt{n^*}$. Therefore, it can be expected that the transition from range 3–5 μm to that of 8–14 μm will not result in any improvement of not only C but the temperature sensitivity as well. The precise calculation shows that such a transition with a limited capacitance of the storage cell even reduces the temperature sensitivity [6].

8. Quantity of information and features of objects for observation

Up to now, we have conducted the comparison of the capabilities of electronic vision systems in information capacity, proceeding from the only condition: the photon exitance of each element of an object can

vary from zero to the maximum value, N_e . Below, the influence of some real features of objects and observation conditions on information capacity are discussed.

The image in daylight and night vision systems being formed by the reflected external radiation, under definite conditions (diffusive reflection, homogeneous irradiance, etc.), the exitance of an object, $N(x, y)$, is linearly related to the spatial distribution of its reflectance averaged over the spectral range of vision system, $R(x, y)$:

$$N(x, y) = R(x, y) N_e. \quad (34)$$

In thermal vision, the image is formed by the intrinsic radiant emission of an object first of all. Under some specific conditions (uniform temperature of an object, a negligible small level of thermal contraradiation from the atmosphere and environmental objects [4]: these factors are analyzed below), the exitance $N(x, y)$ is linearly related to the complement of R , the emissivity $\epsilon = 1 - R$:

$$N(x, y) = \epsilon(x, y) N_e = N_e - R(x, y) N_e. \quad (35)$$

As is seen, in both cases under consideration, the information fields for the image and the reflectance coincide completely. In this case, the sensitivity of vision system to the contrast $\delta R/R$ equals that to the contrast $\delta N_e/N_e$.

In real situations, the total information potential of vision systems often remains to non-used because the range $\Delta\epsilon = \Delta R$ is smaller than the total percentage range. In addition to that, the contrast depends on the spectral range. So, it is known [4] that the mean value of reflectance for visible radiation from natural objects is 10.24%. In the infrared image of natural objects, contrasts usually decrease with increasing the wavelength. In particular, for the spectral range 3–5 μm , values $\epsilon = 0.7$ –0.9 are typical and for that of 8–14 μm , $\epsilon \geq 0.9$ [13]. For the calculation of the information capacity of sceneries with a limited range of changing ΔR , Eq. (1) and all the expressions following from it should be modified: ΔR should be entered under the logarithm symbol, i.e., it should be taken into account that the possible number of gradations in each element is now equal to ΔRK . According to these relationships and Table 1, the decrease in contrast when moving from the range 3–5 μm to that of 8–14 μm is

completely overcome by the increase of the intensity of the thermal radiant emission: $\Delta\epsilon$ decreases by a factor of about 2 to 3 and $\sqrt{N_e}$ becomes ~ 9 times larger. With the said range of variation of $\Delta\epsilon = \Delta R \approx 0.1\text{--}0.3$, the information capacity decreases by ca. 5% to 10% as compared with the value calculated for the whole range, $\Delta R = \Delta\epsilon = 1$.

To some reduction of the contrast of thermal images, thermal contraradiation leads as well, in particular the contraradiation of the atmosphere contributing substantially to the thermal balance of the earth [4,7,8]. The reflected contraradiation of $R(x,y)aN_e$ flux density is added to the intrinsic thermal radiation of objects (the factor a shows what fraction of the object radiation amounts to the contraradiation: under averaged conditions on the earth for the long-wavelength range, $a \approx 0.8276$). Adding the two components and taking into account the relationship $R = 1 - \epsilon$, we obtain for the thermal image:

$$\begin{aligned} N(x,y) &= \epsilon(x,y)N_e + [1 - \epsilon(x,y)]aN_e \\ &= \epsilon(x,y)(1 - a)N_e + aN_e. \end{aligned} \quad (36)$$

The contraradiation aN_e leads to not only the appearance of the ‘pedestal’ but to the decrease of signal in the image conditioned by variations of ϵ by a factor of $1/(1 - a)$ [4] [compare Eqs. (35) and (36)]. This is explained by the fact that both considered components of radiation compensate for each other: in a ‘dark’ point, where the emissivity, ϵ , is small, the share of intrinsic radiation is less, but the share of reflected radiation is higher because the reflectance, $R = 1 - \epsilon$, is greater in this case. In a ‘light’ point, at a greater ϵ , the intrinsic radiation rises, but the reflected one decreases. Now, into Eq. (1) and the equations derived from it, the variation of not the ordinary contrast $\Delta\epsilon = \Delta R$ but the effective contrast $(1 - a)\Delta\epsilon$ should be entered.

In the limit when a approaches unity, both the radiations, intrinsic and contra, completely compensate for each other. With such a balance, the image stops to be dependent on $\epsilon(x,y)$. Actually, it stops to be an ‘image’, turning, with lack of temperature contrast, into the homogeneous background, $N(x,y) \approx N_e$ [Eq. (36)].

In Ref. [4], two typical situations were described: propitious and inconvenient for an observer. The

propitious situation is the observation of the surface of the earth from above the atmosphere in the spectral range 8–14 μm with no clouds. In this case, the contraradiation of the atmosphere can be neglected and so, the contrast in an image practically completely reproduces the contrast of objects in $\Delta\epsilon$, which was shown in the beginning of this section [Eq. (35)]. The other situation is the observation in the same spectral range of vertical objects situated near the surface of the earth when the contrast and, consequently, the number of distinguished gradations decrease by a factor of about 6, $(1 - a_v) = 0.167$ [4]. However, the additional losses in information capacity even in such an inconvenient case will be ca. 8% only, which is explained by ‘the logarithmic effect’, $C \sim \log(1 - a_v)$.

Similarly, the dependence C on other known factors that influence n_e can be observed, namely, the absorption in the atmosphere, daily time, the season and the geographical situation. But the system remains a high-level one, the dependence $C(n_e)$ will have been smoothed and the information capacity of one picture element will have been of the order of one byte.

In the analysis of an image and the features of an object, not only quantity but also the character of information can be important. In the information massif C , the information is contained concerning both the number of picture elements M over the space $R(x,y)$ and the number of the gradations of brightness (levels of contrast), K , in each element. The possibility of a considerable increase in C for vision systems on account of some increase of M was mentioned above. However, in a number of problems, the minimum possible contrast, $\delta R/R$, must be registered while the number of picture elements, M , can be relatively small. In this case, it is purposeless to enhance the resolution of vision system over the required value M , but one should try to obtain the ultimate sensitivity: the system should be designed following the criterion $NEP_{\min}$ but not the $C_{\max}$.

In general, the number of picture elements M can be ‘changed’ by that of gradations K , simultaneously increasing the sensitivity of a system to the contrast of irradiance, too. In order to perform this, the element area, A_e , should be increased, then the value of K rises [Eq. (8)] and the number M falls:

according to Eq. (3), with the frame area, A_f , to be constant, we obtain $M \sim 1/A_e$.

It is obvious that in the limit, both the information capacity and the NEP of a vision system are limited by the fluctuations, which cannot be removed in principle, of the flux of photons that form the optical image in this system. It is convenient for an ideal vision system to be characterized by the specific number, K^* , of the gradations distinguished by it, bringing K to the unit values of A_e , t_i , $\sin^2(\beta/2)$, k_0 . Normalizing Eq. (8), we get, for $\eta = 1$, $F = 1$:

$$K^* = \frac{K k_0}{\sqrt{A_e t_i \sin^2(\beta/2)}} = \sqrt{N_e}, \quad (37)$$

The specific quantity K^* , like the specific quantities of the detectivity, D^* , and the noise equivalent temperature difference, NETD * , [4] are determined by features of an object and conditions of observation. In the given case, K^* is the ratio of the maximum specific signal from an object, N_e , to its noise, $\sqrt{N_e}$. This value, $N_e/\sqrt{N_e} \equiv \sqrt{N_e}$, is also called the dynamic or information potential of an image [3,4]. As is seen, even an ideal electronic-optical system realizes the potential inherent in an object in some measure only. In this case, its efficiency, $\sin^2(\beta/2) A_e t_i$ [Eq. (37)], is determined by the collection of radiation with the objective and the photo-sensitive areas as well as by the accumulation of photocharges in the unit cells.

The result turned out to be interesting and unexpected comparing diverse vision systems regarding the information potential K^* when observing the moon. It is known 7% of the sun radiation incident is reflected from the moon, on average [7]. The rest of the incident sun energy is absorbed by the moon surface and then remitted in the infrared range. In this case, because of a low thermal conductance of the surface of the moon, the remission mainly occurs from the sunlit side, which is heated to 413 K [7]. Thus, the intrinsic long-wavelength radiation from the sunlit side of the moon is $93/7 \approx 13$ times as large as the reflected sunlight in power and the number of IR photons is $13 \times (5785 \text{ K}/413 \text{ K}) = 186$ times as large as that of short-wavelength photons. The contraradiation for the horizontal surfaces on the moon, which practically has no atmosphere, is close to zero. As a result, the information potential K^*

even of the sunlit side of the moon in the IR range turns out to be substantially greater than that in the visible range.

The increase of the information potential of an optical image resulting from the transformation of radiant power into an long-wavelength range appears to be a paradoxical phenomenon: usually, any transformation is accompanied by loss of information. However, in the given case, the transformation undergoes a kind (a channel) of information transfer.

Probably, the long-wavelength range surpasses the visible one in the potential K^* also in remote optical sounding of the solar system planets.

It was first shown in Ref. [4] that in the information potential of the image, thermal vision under the condition of thermal balance of the earth does not yield to the human daylight vision ('the rule of information potentials'). The density of the quanta of long-wavelength radiation under the condition of thermal balance of the earth [7,8] is about $T_s/2T_E$ times as high as that in the short-wavelength range: the factor of 1/2 is due to the fact that the sun quanta are absorbed only on the day illuminated hemisphere and the long-wavelength ones are emitted from the whole surface of the earth. Besides, in the range 8–14 μm , the factor of the use of the long-wavelength-radiation quanta (0.230) is almost 3 times as high as this factor is in the visible spectral range (0.082) [4].

However, owing to the addition of the intrinsic thermal radiation of vertical objects and the contraradiation of both the atmosphere and the earth reflecting from them, the image in the spectral range 8–14 μm is formed, as was mentioned above, only by the $(1 - \alpha_v) = 0.167$ fraction of the quanta received. As a result of the mutual compensation for the above factors, the information potentials of visible and infrared images turn out to be equal.

In this case, the known advantages of observation in the IR range are a weak dependence of the information potential on the time during the day (it should be reminded that the irradiance near the earth surface can change by 9–10 orders of magnitude within this time interval) as well as a smaller dissipation of radiation in mists, fogs and under man-made hindrances. It is obvious that these advantages of the thermal vision are valid for the systems of daylight electronic vision as well.

The conclusion on the equality of the information potentials of visible and IR images under earth conditions is a principle one in our view: in the information volume, the thermal vision can reach the level of the daylight vision, which is known to ensure for people more than 80% of all the information received. Thus, 'the rule of information potentials', in a large measure, determines progress possibilities for practical thermal vision [4].

The calculations in this paper including the derivation of Eqs. (8) and (37) are performed for the maximum level of noise, $n_n = \sqrt{F\eta n_e}$, identical for all channels. Theoretically, the algorithm of the system can be complicated: one can determine 'an individual' noise for each channel depending on the signal level in this channel, ηn , taking it to be equal to $\sqrt{F\eta n}$. It means that after the transition to the specific values and for $\eta = 1$, $F = 1$, over a segment of dN length, $dK^* = dN/\sqrt{N}$ gradations can be distinguished and the specific number of the gradations distinguished by, the system is:

$$K^* = \int_0^{N_e} \frac{dN}{\sqrt{N}} = 2\sqrt{N_e}. \quad (38)$$

Comparing Eqs. (37) and (38), one can see that the potential of the image, K^* , with the mentioned adapted processing algorithm increases by a factor of two, i.e., as if the effective quantity of photons, N_e , rises by a factor of four. It was repeatedly noted above that C very weakly depends on N_e , from which follows that a similar complication of the algorithm for some increase in C to be obtained is an unlikely expedient. But concerning detecting systems, where it is required to enhance K^* , the above-described adapted algorithm is applicable. A more simple intermediate algorithm is used as well: for the 'darkened' fragment of a frame with a relatively small level n'_e , the identical value of noise, $\sqrt{F\eta n'_e}$, is assumed. Then the number of distinguished gradations in this fragment rises by a factor of $\sqrt{n_e/n'_e}$.

Also other algorithms of interelement as well as interframe image processing are worth to consider additionally.

In the general case, an image depends not only on R or ϵ but on other characteristics of objects and observation conditions. For example, at a non-uni-

form temperature, T , of the objects in a frame, onto their infrared image in thermal imagers conditioned by a variation of $\epsilon(x, y)$, the image is put arising on account of a spatial variation of T . In the linearized model for small $\Delta T \ll T$,

$$\begin{aligned} \Delta N(x, y) &= \Delta \epsilon(x, y)(1 - a)N_e + \frac{dN_e}{dT}\Delta T \\ &= \Delta \epsilon(x, y)(1 - a)N_e + \xi \Delta T N_e. \end{aligned} \quad (39)$$

Here, $\xi = (1/N_e)dN_e/dT$ is the relative temperature factor of the thermal radiant emission in the range $0 - \lambda_m$. According to Ref. [6], it is equal to:

$$\xi = \frac{1}{T}(x_m + 1 + \xi), \quad (40)$$

where $x_m = hc/kT\lambda_m$ and ξ is some correction:

$$\xi = \frac{1.6 x_m + 4.8}{x_m^2 + 2 x_m + 2.4}. \quad (41)$$

In order for the calculations to be simplified, the correction ξ can be assumed to be equal to its maximum value for the range $\lambda \ll \lambda_m$. So, at $\lambda_m = 14 \mu\text{m}$, it is 0.4. Then the error in calculation of ξ from Eq. (40) will not exceed 2–3%. For the range $0 - \infty$, one can take $\xi = 2$, this will result in an error of $\sim 30\%$. For the range $8 - 14 \mu\text{m}$ according to Eqs. (40) and (41), we will obtain $\xi = 0.017 \text{ K}^{-1}$.

Eq. (36) makes it possible to evaluate the minimum value $\Delta \epsilon_{\min}$ that an imager with known temperature sensitivity, NETD, can register:

$$\begin{aligned} |\Delta \epsilon|_{\min} &= |\Delta R|_{\min} = \frac{\xi}{1 - a_v} \Delta T = \frac{\xi k_0}{1 - a_v} \text{NETD} \\ &= \frac{0.017 \times 5(0.04 - 0.1)}{0.167} = 0.02 - 0.05. \end{aligned} \quad (42)$$

Here, $\Delta T = k_0 \text{NETD}$ was substituted. The numerical evaluation was done for the range $8 - 14 \mu\text{m}$, $\text{NETD} = 0.04 - 0.1 \text{ K}$, and for the observation of small-size vertical objects situated near the earth surface [4]. For the natural formations on the earth, the typical values of ϵ being equal to $\approx 0.9 - 1$ [13], the mentioned thermal imager is able to distinguish two–five gradations $\Delta \epsilon$, ΔR under the conditions assumed.

Thermal imagers with $\text{NETD} > 0.1 - 0.2 \text{ K}$, under these conditions, do not perceive the picture condi-

tioned by the variations of the emissivities of small-size vertical objects and can be used for revealing somewhat higher or lower temperature of these objects only [4]. Also shown in Ref. [14] is that the ultimate value of NETD for the ‘staring’ thermal imagers sensitive in the spectral range 8–14 μm is close to 10^{-4} K.

Thus, the information capacity in all the considered situations can be taken to be a universal parameter showing not only capabilities of a vision system but also a measure of proximity of a particular equipment to the theoretical limit.

9. Ultimate specific information capacity. Rule of binary channels

Let us express the number of picture elements M in Eq. (1) in terms of the areas of an element, A_e , and the frame, A_f , ($M = A_f/A_e$):

$$C = 0.415 \frac{A_f}{A_e} \log \left[\frac{1}{k_0} \sin \left(\frac{\beta}{2} \right) \sqrt{\frac{\eta}{F} A_e t_i N_e} \right]. \quad (43)$$

The dependence of C on all the parameters of the problem is monotonic (except for the area of a picture element, A_e), and in order for C to be maximized, it is necessary to decrease the values of k_0 , F and to increase η , t_i , N_e , β . The ultimate values of these parameters were already presented above: $k_0 = 5$ (with a permissible error probability of ca. 10^{-9}), $t_i = T_f = 4 \times 10^{-2}$ s (for systems with the TV frame time); $\sin \beta = 0.45$ (with $D:f = 1:1$); $F = 1.37$ (for idealized daylight- and thermal-vision systems) and $F = 1$ (for a night vision system); $\eta = 1$; the values of N_e are given in Table 1. These values will be used below in the calculation of the ultimate value of information capacity. The parameter A_f can generally be eliminated considering the specific capacity (per unit of frame area), $C^* = C/A_f$, is introduced.

Now it remains to consider the dependence $C(A_e)$ and to determine the optimum area of the picture element, A_e .

According to Eq. (43), the information capacity C tends to zero with both a small element area and a large one. In the first case, the argument of the logarithm at some finite value of A_e tends to one

and, consequently, the logarithm itself tends to zero. In the second case, with $A_e \rightarrow \infty$, both the numerator ($\sim \log \sqrt{A_e}$) and the denominator ($\sim A_e$) rise, but the former rises more slowly. And as a consequence of such a non-monotonic dependence, some optimum value $\text{opt } A_e$ has to exist for which the capacity C^* is maximum. Having the derivative dC^*/dA_e being equal to zero, we arrive at the following value of $\ln K$:

$$\ln K = \ln \left[\frac{1}{k_0} \sin \left(\frac{\beta}{2} \right) \sqrt{\frac{1}{F} \text{opt } A_e T_f N_e} \right] = \frac{1}{2}. \quad (44)$$

It follows from Eqs. (43) and (44), that the specific information capacity of electronic imaging systems, with the set value of N_e , rises with the density of the optical channels (with a decrease in dimensions of the elements or with improvement in spatial resolution) up to where the number of gradations in each channel becomes about two and, hence, the capacity of each channel amounts to one bit.

This result is important theoretically for multi-channel electro-optical systems of information transfer and can be formulated as ‘the rule of binary channels’: The information capacity of an electronic vision system is maximum with the ultimate spatial resolution, i.e., in the case when the amount of quanta that is necessary for one bit of information to be transferred is incident on one picture element for the frame time.

As is shown below, ‘the rule of binary channels’ is valid under a relatively low irradiance when the radiation that is necessary for the transfer of one bit of information is incident on a photosensitive element with a size larger than the diffraction limit.

In accordance with Eq. (44), the maximum of C^* is attained with the area of the photosensitive element equal to

$$\text{opt } A_e = (\text{opt } l_e)^2 = \frac{k_0^2 F e}{T_f N_e \sin^2(\beta/2)} = \frac{8375 F}{N_e}. \quad (45)$$

Here, e is the Napierian base. The condition of Eq. (45) determines the minimum quantity of detected photons, $(n_s)_{\min} = k_0^2 F e$, as well.

For the systems of daylight and thermal vision with $N_e = (1-382) \times 10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ (see Table 1), we obtain:

$$\text{opt } l_e = \sqrt{\text{opt } A_e} \approx 0.0005-0.1 \text{ } \mu\text{m} \quad (46)$$

and for night vision with $N_e = N = 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$,

$$\text{opt } l_e = \sqrt{\text{opt } A_e} = 2.9 \text{ } \mu\text{m}. \quad (47)$$

The attainment of the extreme of C^* ($\text{opt } A_e$) is not a success with a great flux of quanta: it is impossible to obtain so high resolution as 0.0005–0.01 μm . It is limited by the diffraction of the objective by the circle of confusion, l_{conf} [15]:

$$(A_e)_{\min} \approx l_{\text{conf}}^2 \approx \left(1.22 \frac{f}{D} \lambda\right)^2 = \frac{3}{2} \left(\frac{f}{D}\right)^2 \lambda^2. \quad (48)$$

Thus, for the calculation of the ultimate value of the specific capacity C^* , we get two relationships. With a small flux of photons (for $\text{opt } l_e > l_{\text{conf}}$), into Eq. (43), $A_e = \text{opt } A_e$ from Eq. (45) should be substituted:

$$C^* = \frac{C}{A_f} = \frac{1}{16 \text{ opt } A_e \ln 2} = \frac{0.09}{\text{opt } A_e} = \frac{N_e}{N^*} \quad (49)$$

where

$$N^* = \frac{16 k_0^2 F \ln 2}{T_f \sin^2(\beta/2)}$$

$$= (0.93-1.27) \times 10^5 < \text{bytes}^{-1} \text{ s}^{-1}.$$

Hence for a night vision system with the typical value $N_e = 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$, we obtain:

$$C^* \approx 10^6 \text{ bytes cm}^{-2}. \quad (50)$$

Under a great flux of photons, $A_e \approx (l_{\text{conf}})^2$ from Eq. (48) should be substituted into Eq. (43):

$$C^* \approx 0.227 \frac{1}{\lambda^2} \left(\frac{D}{f}\right)^2 \log \left[\frac{0.61 \lambda}{k_0} \times \sqrt{\frac{T_f N_e}{F}} \right]. \quad (51)$$

A definite difficulty in the use of the last relationship consists in the choice of the wavelength λ for the calculation. The greatest value of C^* appears to be attained with the infinitely wide spectral range, when $N_e = N$. However, with $\lambda \rightarrow \infty$, we get $C^* \sim 1/\lambda^2 \rightarrow 0$. Therefore, it is reasonable to determine the C^* for real spectral ranges, assuming the long

wavelength cutoff of this range, λ_m , to be as the value λ calculated. Substituting the quantities $\lambda = \lambda_m$, N_e for the ranges 0.45–0.95, 3–5, and 8–14 μm , according to Table 1, we will obtain:

$$C^* = \frac{0.81-1.23}{\lambda^2} = \frac{1}{\lambda^2} \pm 25\%. \quad (52)$$

Now we explain the above-obtained Eqs. (49) and (52). As was already noted above, an electronic vision system, when forming an image signal, should transfer at least two brightness gradations, $K \geq 2$. Hence, the evaluation can be obtained for the minimum permissible signal-to-noise ratio in each channel as well: for small, as compared with the resolution of a system, objects, in accordance with Eq. (8), it should be not less than $Kk_0 = 2 \times 5 = 10$. The precise value of the signal-to-noise ratio is taken from Eq. (44). It happens to be close to the qualitative estimation:

$$\ln K = \frac{1}{2}, \quad K = e^{0.5} \approx 1.65,$$

$$Kk_0 = e^{0.5} \times 5 = 8.25. \quad (53)$$

As is known, [1] for extended objects under visual observation or inside-frame summing up, k_0 decreases to unity.

The set signal-to-noise ratio can be ensured if the number of photons incident upon the photosensitive area for the frame time is not less than the above-calculated value $(n_s)_{\min} = k_0^2 F e$ [Eq. (45)]: this amounts to 70–90 photons per element for small objects and to 3–4 for extended ones.

In Section 3 for the fixed area ($A_e = 30 \times 30 \text{ } \mu\text{m}$) and the typical values of other parameters of the system, the minimum density of quanta emitted by an object, $N_{\min}$ [Eq. (19)], was calculated. Now, for the set density N_e , the permissible size of the area, $\text{opt } A_e \sim 1/N_e$ [Eq. (45)], is found: for a smaller area, no required quantity of photons will be collected. In a frame of unit area ($A_f = 1 \text{ cm}^2$), $M = 1/\text{opt } A_e$ picture elements (channels) will be arranged. With transferring two brightness gradations ($K = 2$), the capacity of one channel will amount to $B = \log_2 K = 1$ bit and the capacity of all the channels will be $C^* = M = 1/\text{opt } A_e$ bits or $C^* = M/8 = 0.125/\text{opt } A_e \sim N_e$ bytes, being the qualitative derivation of Eq. (49).

According to Eqs. (45) and (49), with increasing the density of the flux N_e , the required area of elements, A_e , decreases and both the number of elements arranged on a unit of the frame area, $M = 1/A_e \sim N_e$, and the specific information capacity, $C^* \sim 1/A_e \sim N_e$, increase correspondingly.

Following Eq. (46), at a very high flux, N_e , the required signal-to-noise ratio is ensured even with very small sensitive areas of elements, which are less than the size of the circle of confusion. Then the area is limited by this size and $A_e \approx \lambda^2$ [this is a qualitative evaluation based on Eq. (48) with $f:D \approx 1:1$]. In the case under consideration, the number of the charge carriers accumulated in a channel and the number of brightness gradations are great, which is why the registration of the number K needs a capacity on the order of one byte. Since $M = 1/A_e \approx 1/\lambda^2$ picture elements (channels) go in the frame area equal to a unit of area (1 cm²), the capacity of the system (with the capacity of a channel equal to one byte) does turn out to be equal to the number of channels, $C^* \approx M \approx 1/\lambda^2$, being the physical essence of Eq. (52).

With the use of Eqs. (49) and (52), the ultimate values of specific capacities for all the vision systems under consideration were calculated, and are presented in Table 2. Also the sizes of the photosensitive elements determined from Eqs. (45) or (48) are given. As is seen from Table 2, the maximum specific value C^* is attained at a high level of irradiation and the shortest wavelength, i.e., in the daylight vision system. In a thermal imager for the range 3–5 μm , it is $\sim (5/0.9)^2 \approx 30$ times worse and for 8–14 μm , it is lower by a factor of ~ 170 [the ratio of the wavelength squares amounts to ca. $(14/0.9)^2 \approx 240$ times].

Note that being distinct in Eq. (52), in Eq. (49), C^* does not depend on λ . This leads the value N_e

corresponding to the boundary between the fields of application of Eqs. (49) and (52) to decrease with increasing wavelength of radiation.

One more consequence follows from the relationship $C^* \approx 1/\lambda^2$ [Eq. (52)]: under the limitation of the sizes of photosensitive elements by diffraction and at $D/f \approx \text{const}$, with increase of wavelength, the area of the objective, A_{ob} ($A_{\text{ob}} \sim D^2 \sim f^2 \sim \lambda^2 \approx C/C^* = A_f$), and the volume, V , of the optical system ($V \sim D^2 f \sim \lambda^3$) have to be increased. Only then, the same resolution capability will be ensured in long-wavelength systems with a somewhat greater value of K [$K \sim \sqrt{A_e}$ [Eq. (8)]].

Realization of the said high capabilities of the daylight vision system, i.e., the attainment of the values $C^* \sim 10^8$ bytes/cm², is rather problematical because it is problematical to produce cells with micron dimensions. And cell dimensions of 10 to 20 μm are attainable with the present day level of technology. Therefore, the value $C^* \approx 6.2 \times 10^5$ bytes/cm² given in Table 2 for the range 8–14 μm is a real 'landmark' for developers of electronic vision systems for not only the long-wavelength spectral range but for the visible one as well. This is confirmed by the evaluation of C^* for real photodetector devices with such dimensions of unit cells. So, with $A_f = 1 \times 1 \text{ cm}^2$ and $\sqrt{A_e} = 17 \mu\text{m}$, we get $M = 580 \times 580 = 3.4 \times 10^5$ and according to Eq. (31):

$$C^* = \frac{C}{A_f} = \frac{M}{A_f} = 3.4 \times 10^5 \text{ bytes/cm}^2. \quad (54)$$

The double losses relative to the theoretical limit ($C^* \approx 6.2 \times 10^5$ bytes/cm²) are due to a limited electric capacitance of a storage cell for the photon detectors.

Table 2
Ultimate values of specific information capacity

	System			
	Daylight vision	Night vision	Thermal vision	
Spectral range (μm)	0.45–0.95	0.3–1.8	3–5	8–14
N, N_e (cm ⁻² s ⁻¹)	7.6×10^{16}	$\sim 10^{11}$	10^{16}	8.5×10^{17}
l_{conf}, l_e (μm)	1.1	2.9	6.1	17.1
C^* (bytes/cm ² frame)	10^8	$\sim 10^6$	3.3×10^6	6.2×10^5

10. Electronic vision systems and the eye

Now it is interesting to compare the considered electronic vision systems with the human vision, following the criterion of information capacity. Using Eq. (1), we will find the value C for the eye under a daylight illumination and in the black–white approximation. In Ref. [4], on the base of the analysis of data published, the following parameters of the eye as an optical device were used: the view angle, 12° ; the quantum efficiency, $\eta = 0.01$; the diameter of the cones, $\sqrt{A_e} \approx (1.5\text{--}6) \times 10^{-4}$ cm; the integration time, $t_i = 0.1$ s. Also the parameter N_e changes relative to that for electronic vision systems: the flux of quanta is calculated for the photopic vision curve of the eye in the spectral range $0.4\text{--}0.7 \mu\text{m}$ and equals $2.33 \times 10^{16} \text{ cm}^{-2}$. Only the value $k_0 = 5$ remains the same. According to Eq. (1), with the said values of the parameters, we obtain:

$$C = 0.415 M \log \left[\frac{1}{5} \times 0.1025 \times (2\text{--}6) 10^{-4} \right. \\ \left. \times \sqrt{\frac{0.1}{0.01} 2.33 \times 10^{16}} \right] = (1.37\text{--}1.57) M. \quad (55)$$

This relationship places the eye into one line with high-level electronic vision systems: if the systems with an identical number of picture elements, M , are compared, then the eye surpasses the systems with real photodetector devices in information capacity by 30% to 60% [Eq. (31)], but it yields to a hypothetical thermal imager with an ideal detector device by ca. 20% to 30% [Eq. (18)]. If the number of picture elements for the eye is taken to be equal to the number of the nervous fibres going out of the eye, ca. 10^6 , then in information capacity, with the eye, the high-resolution systems level if their format is $M \geq 1000 \times 1000$. Scanning systems based on linear arrays with $M_e = 2000$ to 5000 have a value C as high as to surpass the eye.

The ultimate value of the information capacity of the image and its dependence on λ [Eq. (52)] obtained above are one more argument in the discussion on whether the spectral ranges of the human vision and the vision of animals are optimum. Formerly, it was assumed that these visions are not

thermal ones, at least, because detectors for the $8\text{--}14 \mu\text{m}$ range had to operate at a low temperature and nature ‘has not been able’ to create any cooled eye. But it was shown later that at room temperature, in principle, radiation could be registered with a sensitivity close to the radiant limit. Theoretically, thermal photodetectors in particular, are able to do this [16]. Thus, the spectral range of sensitivity of the eye can hardly be related to problems of cooling. From the point of view of the results obtained in this paper, the expedience of vision in the spectral range $0.4\text{--}0.7 \mu\text{m}$ can be explained by a high specific information capacity. The diameter of the cones in the human eye (to $1.5\text{--}2 \mu\text{m}$ [13]) is close enough to the diffraction limit [Eq. (48)]. In this case, the value C^* in the visible range turns out to be higher by two orders of magnitude than that in the IR range ($8\text{--}14 \mu\text{m}$) [Eq. (53)]. The gain in minimizing the volume of an optical system turns out to be still larger, at least by one order.

Fragmentary processing of the photosignals from the cones in the ganglion cells does not appear to lead to any essential decrease in information capacity of the vision [Eq. (38)] and the combination of the rods into groups ensures the necessary increase of photosensitive areas under a low illumination [Eq. (45)]. Lastly, some features the vision agree with the two-gradation mode ensuring the maximum value of specific information capacity [Eqs. (43) and (44)].

So, the universal principle of nature: to arrive at the decisions optimum from the point of view of physics is confirmed again.

11. Conclusion

(1) The information capacity of electronic vision systems, C , is first of all determined by the number of picture elements, M , and under a considerable level of irradiation weakly depends on type of a system (daylight or thermal vision), spectral range (for example, $3\text{--}5$ or $8\text{--}14 \mu\text{m}$), quantum yield (intrinsic, extrinsic, or Schottky-barrier photodetectors), on detector configuration (linear or 2D array), and on its other parameters within the real limits of variation. With typical parameters of high-level-vision systems, their ultimate information capacity conditioned by the fluctuations of the flux of the

photons forming an optical image is calculated according to the simplest formula: $C = (1-2)M$ bytes/frame. Higher values of the factor at $M \sim (1.8-2)$ correspond to an ideal photodetector device and lower ones (~ 1) correspond to a real photon detector device, in which the principal cause of the decrease of C is a limited electric capacitance of the storage cell.

Somewhat smaller is the information capacity in a low-level system of night vision: $C \approx (0.4-0.5)M$ bytes/frame.

(2) In the information potential, thermal vision does not yield to daylight vision under averaged conditions of thermal balance on the surface of the earth, when contraradiation leads to a decrease of contrast in the infrared image. This conclusion determines the progress possibilities of practical thermal vision arising now owing to the use of two-dimensional array detectors.

(3) The ultimate specific information capacity C^* of electronic vision systems under a low level of irradiation rises with the density of optical channels up to the value for which the number of gradations in each channel becomes about two ('the rule of binary channels'). In this case, the maximum value of C^* turns out to be proportional to the number of quanta emitted and reflected from a unit of area of an object, N_e , in the spectral range of sensitivity of the detector device and with typical parameters of a system amounts to $C^* = N_e/N^*$ where $N^* \approx 10^5$ bytes⁻¹ s⁻¹.

Under high irradiation conditions, the specific information capacity of electronic vision systems, theoretically, is limited by diffraction. In this case, the frame area should be covered by squares of $\lambda \times \lambda$ size (λ is the wavelength). And the number of these squares will be, with an error of less than 25%, the ultimate information capacity expressed in bytes per frame and 1 cm² of image area.

(4) Nature created the eye to be optimum in information capacity, giving it the spectral range 0.4–0.7 μm : here, in the ultimate case, the specific information capacity is two orders of magnitude

higher and the minimum volume of the optical system is three orders smaller than those for infrared images.

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